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Abstract. Recent experiments at the GEANIE/WNR facility and the University of Kentucky accelerator have yielded strong evidence for a two-gamma excitation in ^{170}Er. This new case can be added to a handful of previously identified examples of two-gamma vibrations, all of them discovered in this decade. In this paper the experimental evidence for a two-phonon excitation ^{170}Er is presented and the current state of understanding of these structures is reviewed in the context of this and other recent findings.

INTRODUCTION

The existence of multiphonon excitations in deformed nuclei has been the subject of continuing debate among both theorists and experimentalist for the last 30 years. On the theoretical side, some models [1] maintain that two-gamma vibrations should only exist in a very few select cases, while others [2,3] present a less pessimistic picture. On the experimental side, the argument has been made [4] that single-phonon hexadecapole excitations can mimic the decay properties of two-phonon gamma states, fueling the controversy over the interpretation of experimental data.

The expected excitation of two-gamma states above the pairing gap where they can lose their character through mixing with a multitude of quasiparticle states is at the heart of both theoretical and experimental difficulties. This simple prediction has far-reaching consequences; to the theorist, it means that the very definition of a $\gamma\gamma$ state must depend on some arbitrary cutoff contribution in the wavefunction, and to the experimentalist, it means that such states will be difficult to observe and to identify unequivocally. However, by their very existence, multiphonon states in deformed nuclei, and their deviations from a simple harmonic oscillator description, provide a direct window into the microscopic basis of collective behavior, and are therefore of keen interest to theorists and experimentalists alike. In what follows, we present a brief review of the properties of recently proposed two-gamma phonon states.

Overview

The history of multiphonon states in deformed nuclei can be traced back to the late 1960s, when early hints [5–7] of such structures were found in ^{154}Gd, ^{168}Er and ^{240}Pu. Subsequent experiments could not confirm these structures, and in 1981 Soloviev and Shirikova [8] presented their case, using the Quasiparticle-Phonon Nuclear Model (QPNM), against the existence of multiphonon states in deformed nuclei. For a decade, their conclusion was borne out as no single irrefutable example of a two-phonon vibration in a deformed system could be found. In 1991, however, with the development of the Gamma-Ray-Induced Doppler-broadening (GRID) technique, the lifetimes of members of the candidate $K^\pi = 4^+$ band in ^{168}Er were finally measured [9], and found to be consistent with theoretical predictions for a $\gamma\gamma$ vibration. In the following years, more cases were discovered, and in 1993 the first example of a nearly harmonic two-phonon excitation was discovered in the well-deformed nucleus ^{232}Th [10]. Recently, this particular case has sparked some controversy when a remeasurement of the angular distribution called into question the $K^\pi = 4^+$ assignment for the $\gamma\gamma$ candidate state [11]. However, an even more recent measurement [12] has confirmed the original assignment.

The $\gamma\gamma$-phonon multiplet results from the coupling of two ($K^\pi = 2^+$) γ phonons, and therefore has two components: one with $K^\pi = 0^+$ and the other with $K^\pi = 4^+$. In practice, high-lying $K^\pi = 0^+$ states frequently have complex structures which are difficult to interpret in a unique manner. The $K^\pi = 0^+$ two-gamma state has been clearly identified in only one nucleus to date: ^{166}Er [13,14]. Therefore this paper will focus on the $K^\pi = 4^+$ member of the doublet. The experimental evidence for $K^\pi = 4^+$ $\gamma\gamma$ states has come from different types of experiments relying on a variety of techniques to measure their decay properties. We have compiled the data for some key signatures from these different sources in Table 1.

Some broad features of $\gamma\gamma$ states can be extracted from this table. The measured energies of the two-phonon states seem to fall into two categories: some, like Os and ^{232}Th are near the harmonic limit of $2\times E_x(2^+_\gamma)$ while the others (^{164}Dy, ^{166,168}Er) display anharmonicities of $\approx$ 2.5-2.8$\times E_x(2^+_\gamma)$. This dichotomy in the energy systematics seems to be correlated with the position of the $4^+_{\gamma\gamma}$ relative to the proton and neutron pairing gaps which are calculated using ref. [15]. and listed in Table 2. The energy ratio $E_x(4^+_{\gamma\gamma})/E_x(2^+_\gamma)$ approaches the harmonic limit when the $4^+_{\gamma\gamma}$ energy is within the gaps and becomes anharmonic when the $4^+_{\gamma\gamma}$ energy lies above one or both of the gaps. The B(E2) are more closely related to the wavefunction of the $\gamma\gamma$ state and therefore do not follow an easily predictable pattern. Generally, the B(E2; $4^+_{\gamma\gamma} \to 2^+_\gamma$) is comparable in order of magnitude to the B(E2; $2^+_\gamma \to 0^+_{gs}$), although their actual ratio varies significantly.

TABLE 1. Experimental data on proposed two-gamma phonon states. Nuclei in parenthesis indicate that transfer reaction data disagree with two-phonon interpretation [4]. Identification of the $4^+_{\gamma\gamma}$ and experimental data are from the main references listed unless otherwise specified. All energies are in keV; all B(E2) are in W.u.[a]

Nucleus	main ref.	$E_x(2^+_\gamma)$	$E_x(4^+_{\gamma\gamma})$	B(E2; $2^+_\gamma \to 0^+_{gs}$)	B(E2; $4^+_{\gamma\gamma} \to 2^+_\gamma$)	B(E2; $4^+_{\gamma\gamma} \to 3^+_\gamma$)
^{106}Mo	[16]	710.4	1434.6			
(^{154}Gd)	[17]	996.3	1645.8	$5.91^{+0.28}_{-0.24}$ [b]		
(^{156}Gd)	[18]	1154.1	1510.5	4.45 ± 0.24 [c]	1.81 ± 0.25 [d]	3.6 ± 0.4 [d]
(^{160}Dy)	[18]	966.2	1694.4	3.40 ± 1.70 [c]	0.18 ± 0.04 [d]	0.17 ± 0.04 [d]
^{164}Dy	[21]	761.8	2173.1	4.27 ± 0.22 [c]	$4.1^{+3.0}_{-1.7}$	$1.5^{+1.8}_{-0.8}$
^{166}Er	[13] [14]	785.9	2028.2	$5.11^{+0.53}_{-0.52}$ [e]	7.4 ± 2.5	9.5 ± 3.2
^{168}Er	[9] [23]	821.2	2055.9	4.73 ± 0.18 [f]	7.1 ± 1.6	4.5 ± 1.6
^{186}Os	[18] [25]	767.5	1351.9	$9.42^{+0.46}_{-0.24}$	$24.9^{+5.9}_{-5.6}$	$40.7^{+5.0}_{-14.1}$
^{188}Os	[18] [25]	633.0	1279.1	$7.29^{+0.06}_{-0.27}$	$12.0^{+1.2}_{-0.8}$	$23.8^{+7.4}_{-2.0}$
(^{190}Os)	[18] [25]	558.0	1163.2	$6.07^{+0.25}_{-0.19}$	10.2 ± 1.3	$41.1^{+3.8}_{-18.5}$
(^{192}Os)	[18] [25]	489.1	1069.6	$5.62^{+0.21}_{-0.10}$	$10.4^{+1.0}_{-1.4}$	$44.8^{+6.2}_{-11.3}$
^{232}Th	[10] [26]	785.3	1414	3.47 ± 0.17	14 ± 4	12 ± 3

[a] $B(E2)_{W.u.} = \frac{1}{4\pi}\left(\frac{3}{5}\right)^2 (1.2A^{1/3})^4 \times 10^{-4}\ e^2b^2$
[b] From ref. [19]
[c] From ref. [20]
[d] From ENSDF
[e] From ref. [22]
[f] From ref. [24]

A variety of models have been used to calculate properties of $\gamma\gamma$ states. These include the Quasiparticle-Phonon Nuclear Model (QPNM) [27], the Multi-Phonon Method (MPM) [3], the Self-consistent Collective Coordinate Method (SCCM) [2], the Dynamic Deformation Model (DDM) [28] and some very recent calculations in the intrinsic-state formalism of the Interacting Boson Approximation (IBA) [29]. Table 3 summarizes theoretical predictions from the harmonic limit, QPNM, MPM and SCCM. In all calculated cases, the models uniformly predict a sizeable anharmonicity in energy which, as was noted above, is not always the case experimentally. The predicted ratios B(E2; $4^+_{\gamma\gamma} \to 2^+_\gamma$)/B(E2; $2^+_\gamma \to 0^+_{gs}$) bracket the corresponding experimental value, with the MPM typically giving the lower bound and with all calculated values a factor of two or more less than the harmonic limit expectation.

TABLE 2. Average pairing gap, calculated using the formalism of ref. [15].

Nucleus	$2\overline{\Delta}_p$ (keV)	$2\overline{\Delta}_n$ (keV)
^{106}Mo	2356	2178
^{154}Gd	2330	1996
^{156}Gd	2256	1936
^{160}Dy	2264	1932
^{164}Dy	2122	1814
^{166}Er	2204	1872
^{168}Er	2134	1814
^{186}Os	2108	1758
^{188}Os	2050	1710
^{190}Os	1990	1662
^{192}Os	1928	1614
^{232}Th	1708	1396

The Erbium Isotopes

The erbium isotopes occupy a priviledged place in the history of $\gamma\gamma$ vibrations with ^{168}Er providing the first confirmed example and ^{166}Er the first–and to date only–case where both the $K^\pi = 0^+$ and $K^\pi = 4^+$ members of the $\gamma\gamma$ doublet have been identified and characterized [13,14]. Part of the reason for these landmark successes can be attributed to the position of these isotopes in the nuclear chart which makes them easily accessible by non-selective reactions such as (n,γ) and $(n,n'\gamma)$.

Soloviev et al. have proposed an explanation [33] for the existence of the $\gamma\gamma$ $K^\pi = 4^+$ state in ^{166}Er. The authors assert that a fortuitous dearth of $K^\pi = 4^+$ states near the energy of the unperturbed $\gamma\otimes\gamma$ level, along with a small value of the coupling between one- and two-phonon states combine to minimize the fragmentation of the $\gamma\gamma$ $K^\pi = 4^+$ level. In ^{168}Er the situation is not as clear: in the QPNM [1] only 30% of the wavefunction of the $K^\pi = 4^+$ state at 2055 keV is attributed to the coupling of two γ phonons. The largest contribution (60%) is due to the one-hexadecapole phonon structure. By comparison, the two-gamma-phonon component in ^{166}Er represents 73% of the $K^\pi = 4^+$ wavefunction. There are currently no published predictions for $\gamma\gamma$ states in ^{170}Er.

THE EXPERIMENTAL CASE FOR ^{170}ER

Based on the successful cases of ^{166}Er and ^{168}Er, a search for $\gamma\gamma$ vibrations was undertaken in the heaviest stable erbium isotope, ^{170}Er. This search was begun with the newly assembled GEANIE spectrometer [34], and a candidate for the $K^\pi = 4^+$ $\gamma\gamma$ state was identified. A follow-up experiment was carried out at the University of Kentucky accelerator to measure the lifetime of this candidate state.

The GEANIE Experiment

In March 1997, ^{170}Er was studied using the $(n,n'\gamma)$ reaction. A white neutron source with energies ranging from about 1 MeV to over 200 MeV is produced by the LANSCE/WNR linac at a 6% duty cycle through proton spallation of a ^{nat}W target. A flux of $\approx 10^6$ neutrons/cm^2/s spread over all energies > 1 MeV was delivered onto a sample of 8g of 99.9%-isotopically-enriched ^{170}Er in oxide powder form, located 20.34 m from the spallation target. Gamma rays from the reaction were observed using the GEANIE spectrometer which at the time of the experiment included 13 coaxial and 7 planar detectors. Both gamma-ray energy and corresponding neutron time-of-flight (TOF) were recorded for each event. A 55-hour run was carried out in this configuration.

The data from the coaxial detectors were sorted into a gamma-ray energy vs. neutron energy matrix, with the neutron energy obtained from the TOF information. The matrix was searched for a pair of gamma rays with energies $E_\gamma^{(1)}$ and $E_\gamma^{(2)}$ and a single corresponding neutron threshold energy at E_n consistent with the

TABLE 3. Theoretical predictions of the $4^+_{\gamma\gamma}$ state properties. QPNM calculations are taken from [31] for ^{156,158}Gd and from [1] for ^{162,164}Dy and ^{166,168}Er, MPM calculations are from ref. [3], and SCCM results from ref. [2]. B(E2) ratios in the harmonic limit are calculated using eq. (4-91) and (4-92) in ref. [30]

Nucleus	Model	$E_x(4^+_{\gamma\gamma})$ (keV)	$\frac{E_x(4^+_{\gamma\gamma})}{E_x(2^+_\gamma)}$	B(E2; $4^+_{\gamma\gamma} \to 2^+_\gamma$) (W.u.)	$\frac{B(E2;4^+_{\gamma\gamma}\to 2^+_\gamma)}{B(E2;2^+_\gamma\to 0^+_{gs})}$
^{156}Gd	Harmonic		2		2.78
	QPNM[a]				
^{158}Gd	Harmonic		2		2.78
	QPNM[a]				
^{162}Dy	Harmonic		2		2.78
	QPNM[a]				
	SCCM	2248	2.50	10.5	1.86
	MPM	2302	2.64		0.59
^{164}Dy	Harmonic		2		2.78
	QPNM[b]	2150	2.80	7.65	1.7
		2230	2.80	4.09	1.0
	SCCM	2007	2.64	11.6	1.83
	MPM	2135	2.87		0.55
^{164}Er	Harmonic		2		2.78
	SCCM	2157	2.51	10.5	1.89
	MPM	2324	2.74		0.52
^{166}Er	Harmonic		2		2.78
	QPNM	2050	2.56	9.2	1.8
	SCCM	2021	2.57	10.6	1.89
	MPM	2152	2.82		0.57
^{168}Er	Harmonic		2		2.78
	QPNM	2000	2.40	3.18	0.73
	SCCM	2080	2.54	8.4	1.89
	MPM	2237	2.80		0.53
^{186}Os	Harmonic		2		2.78
	SCCM	1770	2.30	12.6	2.00
^{188}Os	Harmonic		2		2.78
	SCCM	1589	2.51	13.9	1.94
^{190}Os	Harmonic		2		2.78
	SCCM	1464	2.63	13.5	1.89
^{192}Os	Harmonic		2		2.78
	SCCM	1313	2.69	12.8	1.89

[a] QPNM predicts dominant hexadecapole structure for lowest calculated $K^\pi=4^+$ bandheads
[b] both parameter choices which predict $\gamma\gamma$ for the first $K^\pi = 4^+$ are listed

decay of a single state to the lowest two members of the γ band at $E_x(2^+_\gamma) = 934$ keV and $E_x(3^+_\gamma) = 1010$ keV. This translates into the conditions:

$$E_\gamma^{(1)} + 934keV = E_n$$
$$E_\gamma^{(2)} + 1010keV = E_n$$

The gamma-ray pair ($E_\gamma^{(1)} = 1518$ keV,$E_\gamma^{(2)} = 1441$) occurring at a threshold energy $E_n \approx 2.45$ MeV was found to satisfy these criteria best. The excitation functions for these two gamma rays are shown in Figure 1.

An intensity ratio was calculated from these excitation functions and is plotted in Figure 2 as a function of incident neutron energy. Despite large experimental uncertainties, the ratio is consistent with the $K^\pi = 4^+$ assignment. The 1518 keV line had to be separated from another line less than a FWHM away, and therefore the ratio is contaminated. The quantity plotted in Figure 2 represents an upper bound to the actual intensity ratio.

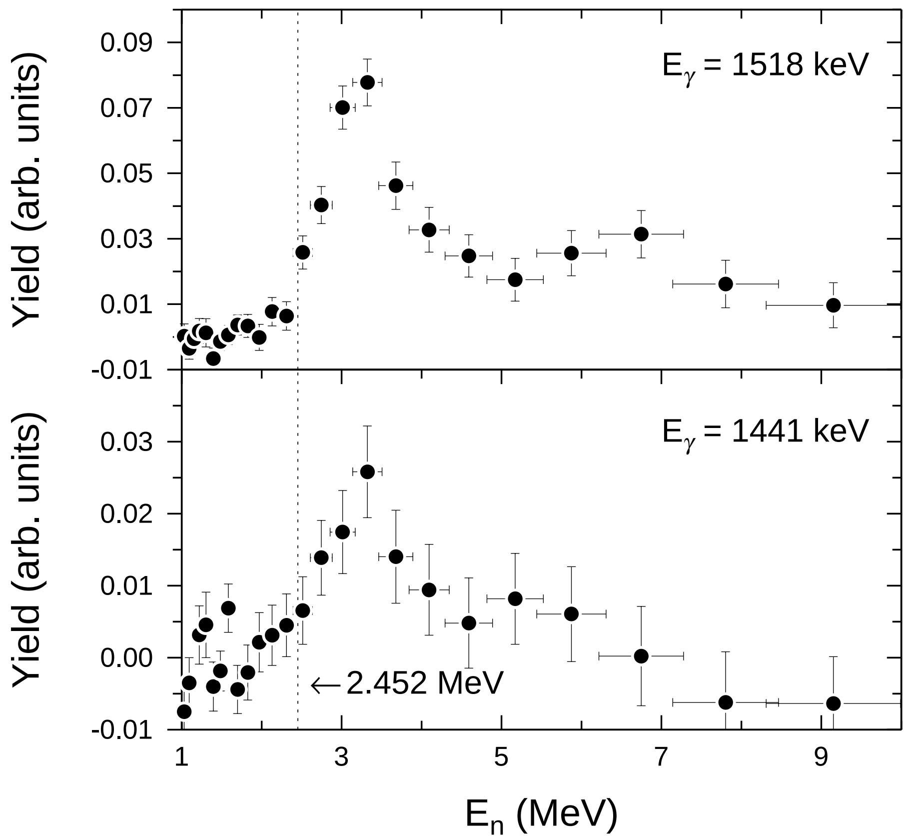

FIGURE 1. Excitation functions for the 1441 keV and 1518 keV gamma rays from GEANIE data.

The Kentucky Experiment

After the initial identification of a $\gamma\gamma$ candidate state, a follow-up experiment was carried out at the University of Kentucky to measure its lifetime using the Doppler-Shift Attenuation Method (DSAM) [35]. Monochromatic 2.7 MeV neutrons were produced by the reaction ^{3}He(p,n) with $E_p = 3.5$ MeV. A sample of 56 g of 99% isotopically enriched ^{170}Er in oxide powder form was suspended in the neutron flux. A single 52% germanium detector at ≈ 1 m from the sample was used to observe gamma rays from the reaction. The gamma-ray sources ^{24}Na and ^{137}Cs were placed near the detector for in-beam calibration. A seven-day run was carried out in March 1998 with the detector rotated through 11 distinct angles. This experiment was preceded by a 5-day coincidence measurement at $E_n = 3.4$ MeV using the KEGS array [36].

The coincidence data were used to confirm the placement of the 1441 and 1518 keV gamma rays. Gates on these lines are shown in Figure 3: the spectra reveal several contaminants for the 1518 keV line which are tentatively placed in the partial level scheme in Figure 4. Most of these contaminants do not pose serious obstructions to the analysis; they are either weak, originate from higher-spin off-yrast states which are not as strongly populated in the $(n, n'\gamma)$ reaction, or are sufficiently different in gamma-ray energy to be distinguished from the line of interest. There is one exception, however for the ≈ 1519 keV gamma ray feeding the 2^+ member at $E_x = 960$ keV of the $K^\pi = 0^+$ band. This line originates from a level less than 30 keV higher than the $\gamma\gamma$ candidate. The contaminant gamma-ray energy is only about 1 keV higher than the line of interest. In the DSAM analysis, the resolution of the germanium detector proved inadequate to separate the two lines. Consequently, our analysis has focused on the 1441 keV candidate $4^+_{\gamma\gamma} \rightarrow 3^+_\gamma$ line.

In addition to the standard sources ^{24}Na and ^{137}Cs, previously well-known lines in ^{170}Er were used for calibration. We also used some lines precisely measured during our experiment using an in-beam ^{226}Ra calibration source with an ^{170}Er spectrum taken at a lower incident neutron energy of 2.3 MeV. In all, 61 lines were selected for energy calibration, with most of them in the range of 200-1500 keV. A nonlinearity for the system

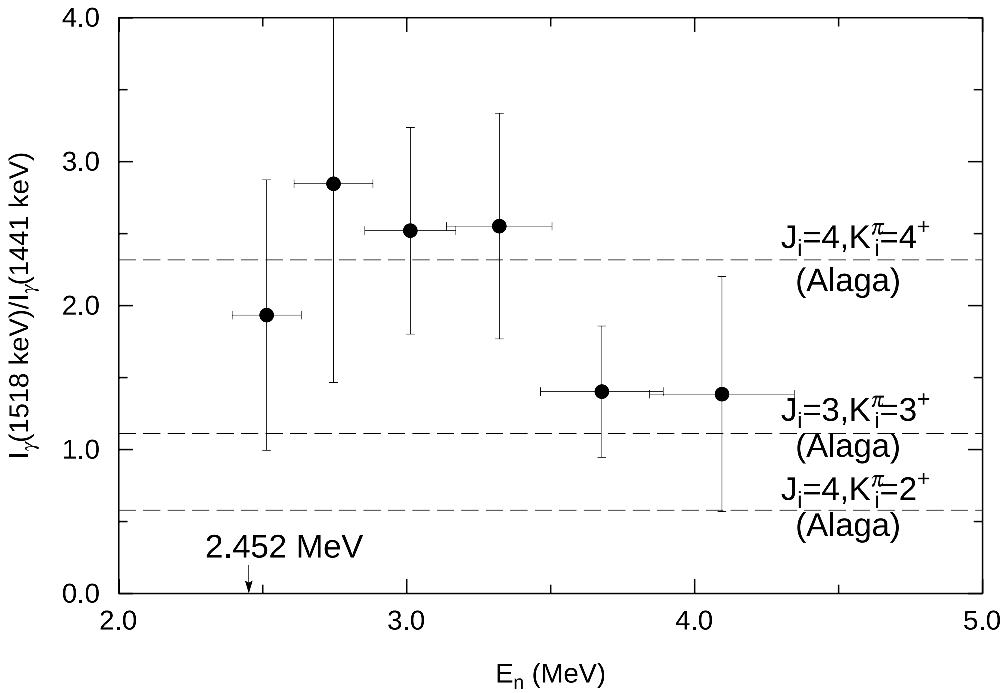

FIGURE 2. Intensity branching ratio from GEANIE data. Also shown are the expected intensity ratios from Alaga rule assuming different values of the K quantum number for the parent state.

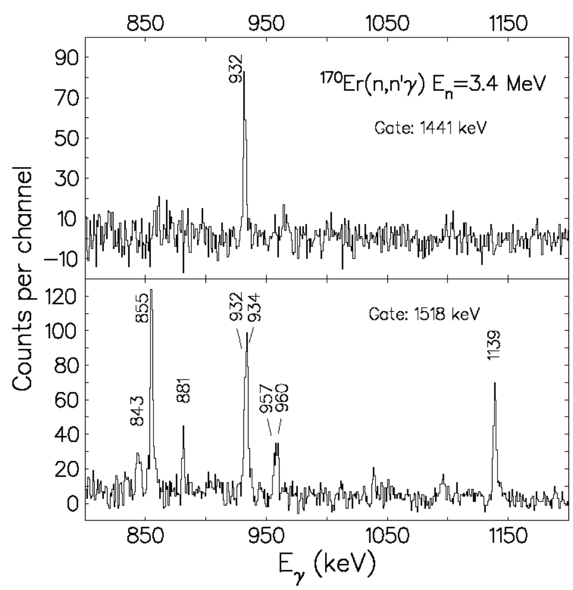

FIGURE 3. Gates on the 1441 and 1518 keV gamma rays from the KEGS coincidence run.

was extracted at each angle by fitting the residual from a linear calibration with a fifth-order polynomial. In this way, the Doppler-shifted energies of the 1441 keV gamma ray could be determined to better than one part in 10000.

Lifetimes were extracted for known states previously studied [37] using nuclear resonance fluorescence to test the calibration. The results are summarized in Table 4. The agreement is excellent for both gamma rays depopulating the level at E_x = 1825 keV, good for the 2054 keV gamma ray from the level at E_x = 2133 keV and poor for the 2133 keV gamma ray from that same level. It should be noted however that the 2133 keV

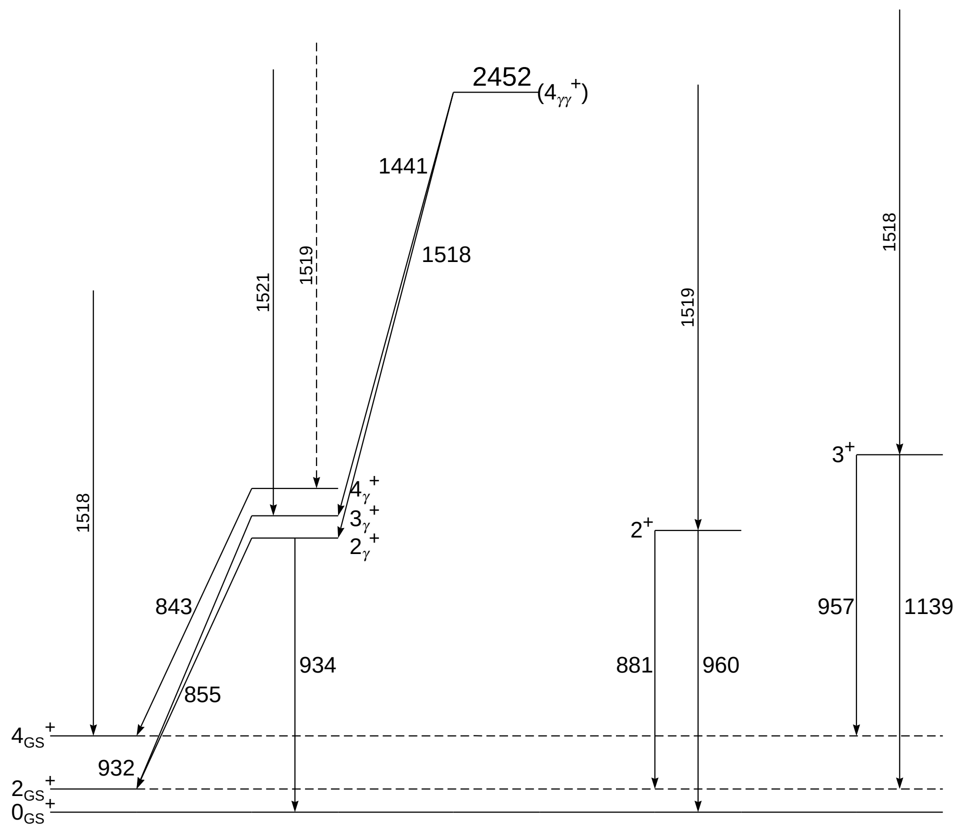

FIGURE 4. Partial level scheme for ^{170}Er showing contaminants for the 1518 keV line.

gamma ray lies within a 230 keV gap between the last two calibration lines and its Doppler shift can therefore not be reliably extracted.

TABLE 4. Lifetimes from our data for some known [37] dipole excitations.

E_x (keV)	τ (fs) (accepted)	E_γ (keV)	τ (fs) (our value)
1825	20.7 ± 3.4	1746	$20.9^{+2.4}_{-1.9}$
		1825	$21.8^{+3.4}_{-1.9}$
2133	173 ± 41	2054	129^{+35}_{-31}
		2133	61^{+8}_{-8}

The Doppler shift of the 1441 keV line is shown in Figure 5 and corresponds [35] in our experimental setup to a lifetime of 84^{+37}_{-24} fs. In order to calculate a corresponding B(E2; $4^+_{\gamma\gamma} \rightarrow 2^+_\gamma$), the relative intensities of decays out of the $4^+_{\gamma\gamma}$ level are required. If we assume the decay out proceeds primarily to the 2^+_γ and 3^+_γ states with relative intensities following the Alaga rule, as suggested by the GEANIE data, we find:

$$\begin{gathered} B(E2; 4^+_{\gamma\gamma} \rightarrow 2^+_\gamma) = 15.0^{+6.1}_{-4.6}\ W.u. \\ \frac{B(E2; 4^+_{\gamma\gamma} \rightarrow 2^+_\gamma)}{B(E2; 2^+_\gamma \rightarrow 0^+_{gs})} = 4.08^{+1.83}_{-1.34} \end{gathered} \tag{1}$$

This B(E2) value is larger than would be expected in the harmonic limit (2.78 W.u.). However, as was noted above, the Alaga branching ratio, which is suggested by the GEANIE data, may be an overestimate. Few of the observed $\gamma\gamma$ states in other nuclei follow the Alaga rules in their decays. If we use instead the branching ratio found in ^{166}Er, the B(E2) values become:

$$B(E2; 4^+_{\gamma\gamma} \to 2^+_\gamma) = 10.9^{+4.3}_{-3.4}\ W.u.$$
$$\frac{B(E2; 4^+_{\gamma\gamma} \to 2^+_\gamma)}{B(E2; 2^+_\gamma \to 0^+_{gs})} = 2.96^{+1.30}_{-0.97} \tag{2}$$

which is significantly closer to the decay properties of observed $\gamma\gamma$ states in other nuclei. A detailed level scheme of ^{170}Er is currently being assembled from the KEGS coincidence data and could shed some light on the decay pattern of the candidate $\gamma\gamma$ state in ^{170}Er.

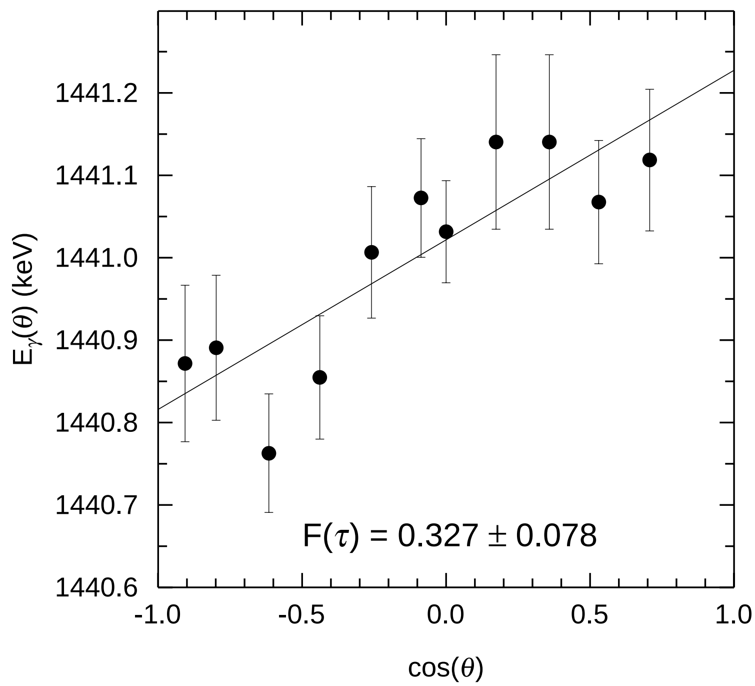

FIGURE 5. Measured Doppler shift for the 1441 keV line.

CONCLUSION

A search for $\gamma\gamma$ vibrations in ^{170}Er has yielded a strong candidate for the $K^\pi = 4^+$ member of the multiplet. Two gamma rays with energies of 1441 keV and 1518 keV have been observed depopulating the candidate state at 2452 keV and feeding the γ band's 3^+ and 2^+ states respectively. A lifetime of 84^{+23}_{-37} fs was measured for the state from the Doppler shift of the 1441 keV gamma ray which, assuming a branching ratio similar to ^{166}Er yields a $B(E2; 4^+_{\gamma\gamma} \to 2^+_\gamma)/B(E2; 2^+_\gamma \to 0^+_{gs}) = 2.96^{+1.30}_{-0.97}$, close in value to other observed $\gamma\gamma$ phonon decays. The value is still somewhat larger than in ^{166,168}Er; however, the calculation assumes no other decays out of the $\gamma\gamma$ state, which is known not to be the case in either ^{166}Er or ^{168}Er. Additional decay paths would further lower the ratio, bringing it more in line with experimental and theoretical values for ^{166,168}Er. The ongoing analysis of coincidence data from the Kentucky experiment might reveal these decay paths.

Encouraging though these results may be, a word of caution is warranted with regards to the role of hexadecapole modes in this structure. There is currently no transfer information available for ^{170}Er. Several β-decay experiments have been performed to study many levels in this nucleus although our candidate state has not been observed before. Transfer and β-decay data for this nucleus would be a welcome and necessary addition in identifying the structure of our candidate state and building a stronger case for a $K^\pi = 4^+$ $\gamma\gamma$ state.

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REFERENCES

1. Soloviev, V.G., *et al.*, *Intl. J. Mod. Phys.* **E6**, 437-473 (1997).
2. Matsuo, M., and Matsuyanagi, K., *Prog. Theor. Phys.* **78**, 591-608 (1987).
3. Jammari, M.K., and Piepenbring, R., *Nucl. Phys.* **A487**, 77-91 (1988).
4. Burke, D.G., *Phys. Rev. Lett.* **73**, 1899-1902 (1994).
5. Meyer, R.A., *Phys. Rev.* **170**, 1089 (1968).
6. Michaelis, W., *et al.*, *Nucl. Phys.* **A150**, 161-186 (1970).
7. Schmorak, M.R., *et al.*, *Phys. Rev. Lett.* **24**, 1507-1511 (1970).
8. Soloviev, V.G., and Shirikova, N. Yu, *Zeit. Phys* **A301**, 263-269 (1981).
9. Börner, H.G., *et al.*, *Phys. Rev. Lett.* **66**, 691-694 (1991).
10. Korten, W., *et al.*, *Phys. Lett.* **B317**, 19-24 (1993).
11. Gerl, J., *et al.*, *Prog. Part. Nucl. Phys.* **38**, 79-85 (1997).
12. Martin, A., *et al.*, manuscript in preparation.
13. Fahlander, C., *et al.*, *Phys. Lett.* **B388**, 475-480 (1996).
14. Garrett, P.E., *et al.*, *Phys. Rev. Lett.* **78**, 4545-4548 (1997).
15. Jensen, A.S., *et al.*, *Nucl. Phys.* **A431**, 393-418 (1984).
16. Guessous, A., *et al.*, *Phys. Rev. Lett.* **75**, 2280-2283 (1995).
17. Wu, X., *et al.*, *Phys. Rev.* **C49**, 1837-1844 (1994).
18. Wu, C.Y., and Cline, D., *Phys. Lett.* **B382**, 214-219 (1996).
19. Wollersheim, H.J., and Elze, Th.W., *Zeit. Phys.* **A280**, 277-279 (1977).
20. McGowan, F.K., and Milner, W.T., *Phys. Rev.* **C23**, 1926-1937 (1981).
21. Corminboeuf, F., *et al.*, *Phys. Rev.* **C56**, R1201-1205 (1997).
22. Fahlander, C., *et al.*, *Nucl. Phys.* **A537**,183-206 (1992).
23. Oshima, M., *et al.*, *Phys. Rev.* **C52**, 3492-3495 (1995).
24. Baktash, C., *et al.*, *Phys. Rev.* **C10**, 2265-2267 (1974).
25. Wu, C.Y., *et al.*, *Nucl. Phys.* **A607**, 178-234 (1996).
26. Korten, W., *et al.*, *Zeit. Phys.* **A351**, 143-147 (1995).
27. Soloviev, V.G., *Theory of Atomic Nuclei. Quasiparticle and Phonons*, Bristol and Philadelphia, Institute of Physics Publishing, 1992.
28. Kumar, K., *Nuclear Models and the Search for Unity in Nuclear Physics*, Norway, Universitetforlaget, 1984.
29. Garcia-Ramos, J.E., *et al.*, *Nucl. Phys.* **A637**, 529-536 (1998).
30. Bohr, A., and Mottelson, B.R., *Nuclear Structure Vol. II*, Reading, Massachusetts, W.A. Benjamin Inc., 1975.
31. Soloviev, V.G., *et al.*, *Nucl. Phys.* **A568**, 244-264 (1994).
32. Soloviev, V.G., and Sushkov, A.V., *Zeit. Phys.* **A345**, 155-161 (1993).
33. Soloviev, V.G., *et al.*, *Phys. Rev.* **C51**, 551-558 (1995).
34. Becker, J.A., and Nelson, R.O., *Nucl. Phys. News Intl.* **7**, 11-14 (1997).
35. Belgya, T., *et al.*, *Nucl. Phys.* **A607**, 43-61 (1996).
36. McGrath, C.A., *et al.*, *Nucl. Instr. and Methods*, in press.
37. Maser, H., *et al.*, *Phys. Rev.* **C53**, 2749-2762 (1996).